Recent Variability in Surface Water Inundation within Arctic Permafrost Zones: Potential Implications for Regional Methane Emissions

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Introduction
Surface water inundation strongly influences methane (CH4) emissions in the pan-Arctic permafrost regions. Although wet conditions favor methanogenesis, the rate of anaerobic decomposition is strongly regulated by temperature. Periods of drying and warming can substantially increase regional CH4 contributions, whereas cooling or drying may reduce the magnitude of emissions. We examine recent (2003-2011) variability in surface water extent across the North American and Eurasian permafrost zones using satellite passive microwave remote sensing retrievals of fractional open water (Fw) derived from Advanced Microwave Scanning Radiometer for EOS (AMSR-E) 18.7 and 23.8 GHz brightness temperatures. The daily AMSR-E Fw retrievals sense sub-grid scale (25-km resolution) inundated areas and are insensitive to solar illumination and signal attenuation from clouds, smoke, and other atmospheric effects which constrain optical remote sensing. Potential changes in CH4 emissions corresponding to Fw and temperature variability are evaluated using a modification of the Joint UK Land Environment Simulator (JULES) wetland CH4 emission model. In addition to the AMSR-E Fw retrievals, model inputs include mean daily soil temperatures obtained from GMAO MERRA reanalysis and surface meteorological carbon pools derived using a Level 4 carbon (L4_C) algorithm developed for the NASA Soil Moisture Active Passive (SMAPI) mission.

JULES CH4 Emissions Model
\[ Fw(C)_4 = k(C)_4 - Fw(C)_{net} \cdot Q_{o}(T_{soil} - 273.15) \]

The JULES model estimates CH4 fluxes according to sub-grid scale Fw area, surface (\( C_{soil} \)) soil temperature (\( T_{soil} \)), and soil organic carbon (Bartlett et al., 2012). The emissions rate constant \( k(C)_4 \) is 6.4 x 10^{-4} d^{-1} and the temperature dependency of methanogenesis is represented by a Q10 factor (\( Q_{10} = 3.4 \cdot 10^{-5} \)). For this study, input carbon was provided using surface metabolic carbon pools (\( C_{net} \)) derived using a Level 4 carbon (L4_C) algorithm developed for compatibility with satellite remote sensing retrievals and reanalysis records. Daily T_{soil} (K) records were obtained from the Goddard Earth Observing System Data Assimilation System (GES-D) MERRA archive with 0.5 x 0.6° spatial resolution. Sub-grid scale inundated surface area was defined using mean and maximum monthly AMSR-E Fw values (25 km resolution; Jones & Kimball, 2011). Regional variability in AMSR-E Fw and T_{soil} and corresponding changes in summer (May-August) CH4 emissions, were evaluated for 2003-2011.

Variability in pan-Arctic Surface Inundation
Surface water inundation in the pan-Arctic permafrost zones is characterized by substantial seasonal and interannual variability. Monthly mean AMSR-E Fw anomalies (left) show large fluctuations in summer inundation occurring in Canada (in black) and Alaska (in red) relative to Eurasia (in grey). Drier surface conditions occurred in 2004 and 2009 throughout the north, reflected in the negative Fw anomalies. Wetter periods in North America include 2005, 2006 and 2009 through 2010. For Eurasia, an increase in Fw inundation area is observed in summer 2007 and early spring 2011.

Regional Constraints on Summer CH4 Emissions

Inputs into the JULES model include inundation area derived from AMSR-E Fw. MERRA T_{soil} and surface \( C_{net} \) which provides available carbon substrate for CH4 production. Although mean summer T_{soil} and \( C_{net} \) for the 2003-2011 period are highest in southern Siberia and the western Canadian Shield region (left), a majority of permafrost zone CH4 emissions occur within wetlands and complexes in Canada, coastal Alaska, and the Ob-Yenisey and Volga river lowlands. Fw inundation extent is widespread in these regions throughout the non-frozen season. Elsewhere, CH4 contributions are more prevalent following late spring snow and ice melt, and are greatly reduced by regional summer drying.

Model Simulation Results

Estimated Monthly CH4 Fluxes

Mean summer (2003-2011) CH4 fluxes from the JULES model simulations (above) reflect strong surface temperature controls on gas emissions within permafrost landscapes. In April, frozen surface water minimizes Fw and CH4 fluxes. The northward progression of warming is observed in May and June, with peak CH4 emissions in July and August. Summer fluxes are highest (>150 mg C m^{-2} d^{-1}) within the CN Mackenzie River basin and southeastern Siberia, which reflect a combination of warmer temperatures and higher \( C_{net} \). Without constraining regional Fw by Fw area, the total summer (May through August) CH4 emissions averaged 97 Tg C. This decreases to 47 Tg C, respectively, when the daily CH4 fluxes are constrained to inundated surfaces represented by the mean and maximum monthly Fw records.

Regional Changes in Surface Controls and Summer CH4

Impacts of Climate Variability on Permafrost CH4 Emissions

Model simulations show relative stability in CH4 emissions for pan-Arctic permafrost regions, but also reflect interannual variability in Fw inundation and temperatures (above). Relative to Eurasia, larger CH4 fluctuations in Canada reflect greater Fw inundation extent and corresponding sensitivity to summer temperature changes. The peak (p<0.07) decrease in Alaska CH4 emissions reflects regional cooling. Summer Fw and T_{soil} anomalies (below) illustrate regional differences in climatic variability and the potentially contrasting influence on CH4 emissions; this is particularly evident in 2004 where summer warming in Alaska offsets lower Fw inundation, resulting in increased CH4 fluxes.

Study Summary

• The 2003-2011 AMSR-E Fw record indicates large interannual variability in pan-Arctic summer surface inundation, and widespread wetting throughout the continuous permafrost zone. Although localized wetting corresponds to changes in surface temperature, as was observed in this study, it may also be influenced by shifts in precipitation and permafrost degradation.

• Although the major wetlands complexes in Canada and Russia were the primary contributors to CH4 fluxes, increases in summer CH4 fluxes throughout northern Siberia coincide with regional wetting. In comparison, decreases in CH4 emissions in Alaska and western Eurasia correspond to regional surface cooling.

• This study highlights the dynamic surface temperature and Fw inundation changes within pan-Arctic permafrost regions. The potentially contrasting influence of temperature and surface moisture on regional CH4 emissions underscores the importance of monitoring these two factors to better characterize and constrain regional CH4 emissions within the northern high latitudes.

References & Acknowledgement

This work was conducted at the University of Montana under contract to the National Aeronautics and Space Administration, NASA Making Earth System Data Records for Use in Research Environments (MEASUREs) program. Bartlett, A. A., M. Trofimov, G. Hayman, D. Sablot, S. Scholte, D. Clarke, and E. Raths. 2012. Detection of wetland dynamics with EUMETSAT ASAR in support of methane monitoring at high latitudes. Geoscientific Solutions 9, 743-754.

